

# A runaway collision in a young star cluster as the origin of the brightest supernova

Simon F. Portegies Zwart  
Astronomical Institute ‘Anton Pannekoek’,  
University of Amsterdam, Kruislaan 403

and

Institute for Computer Science,  
University of Amsterdam, Kruislaan 403

spz@science.uva.nl

Edward P.J van den Heuvel  
Astronomical Institute ‘Anton Pannekoek’,  
University of Amsterdam, Kruislaan 403

and

Kavli Institute for Theoretical Physics,  
University of California Santa Barbara, CA 93106-4030, USA

edvdh@science.uva.nl

February 2, 2008

Supernova 2006gy in the galaxy NGC 1260 is the most luminous one recorded <sup>1, 2, 3, 4</sup>. Its progenitor might have been a very massive ( $> 100 M_{\odot}$ ) star <sup>5</sup>, but that is incompatible with hydrogen in the spectrum of the supernova, because stars  $> 40 M_{\odot}$  are believed to have shed their hydrogen envelopes several hundred thousand years before the explosion <sup>6</sup>. Alternatively, the progenitor might have arisen from the merger of two massive stars <sup>7</sup>. Here we show that the collision frequency of massive stars in

a dense and young cluster (of the kind to be expected near the center of a galaxy) is sufficient to provide a reasonable chance that SN 2006gy resulted from such a bombardment. If this is the correct explanation, then we predict that when the supernova fades (in a year or so) a dense cluster of massive stars becomes visible at the site of the explosion.

The presence of hydrogen in supernova SN 2006gy is hard to reconcile with the explosion of a  $\gtrsim 40M_{\odot}$  star, as such a star loses its hydrogen-rich envelope several hundreds of thousands of years before the star explodes <sup>6</sup>. Also the location of the supernova, at a projected distance of about 1'' ( $\sim 350$  pc) from the nucleus of the host galaxy NGC 1260 is remarkable.

A merger between a very massive ( $> 100M_{\odot}$ ) hydrogen-depleted star that already had a core in an advanced phase of helium burning, with a hydrogen rich main-sequence star of 10 to 40  $M_{\odot}$ ,  $10^4$  to  $10^5$  years prior to the supernova explosion may explain the unusual brightness of the supernova, the presence of the hydrogen in the interstellar medium surrounding the supernova and the presence of hydrogen in the supernova itself <sup>7, 5</sup>.

The existence of young star clusters which are in a state of dynamical core collapse is crucial for the proposed scenario. During core collapse and the subsequent post-core collapse evolution of the star cluster a runaway collision product can grow <sup>8</sup>, and even though the star is likely to be much more extended than usual, subsequent bombardment will result in a net increase in mass <sup>9</sup>. Eventually the massive star is expected to prostrate to a black hole of intermediate mass <sup>10, 11</sup>. The supernova in which the black hole forms is likely to be unusually bright with some hydrogen in its envelope left-over from the last collision.

The inner few hundred parsec around the center of the Milky Way is populated with several bright and dense star clusters, of which the Arches cluster <sup>12</sup> and Quintu-

plet <sup>13</sup> are the most well known, but many others exist <sup>14, 15, 16</sup>. The proximity of the Galactic center and the depth of the potential well of the bulge causes these clusters to be denser than elsewhere in the Galaxy <sup>17</sup>.

The SB/SB0 host galaxy NGC 1260 appears rather ordinary <sup>18</sup>, though the presence of a dust lane and of HII emission near its center suggests that a recent burst of star formation occurred near its center <sup>7, 5</sup>. We estimate, taking an intergalactic extinction of  $A \simeq 0.43 \text{ mag}$  <sup>19</sup> into account, that within the observed isophotal magnitude  $B_{25} \simeq 16''$  ( $\sim 5.6 \text{ kpc}$ ) <sup>19</sup> and adopting  $M/L_B \propto L^{0.3}$  <sup>20</sup>, NGC 1260 has a mass of  $M(5.6 \text{ kpc}) \simeq 3 \times 10^{10} \text{ M}_\odot$ .

Assuming that the mass enclosed within a radius  $R$  from the center of NGC 1260 is, like in the Milky Way <sup>21</sup> described with  $M(R) = \mu R^{1.2}$ , but for NGC 1260  $\mu \simeq 9.5 \times 10^5 \text{ M}_\odot$ . We can then calculate the lower limit to the tidal radius <sup>22</sup> for a cluster of mass  $m$  in a circular orbit at distance  $R$  from the center of NGC 1260.

Star clusters that experience core collapse before the most massive stars have left the main sequence can grow a supermassive star via collision runaway <sup>8, 23, 24, 25</sup>. The mass which can then grow within  $\lesssim 3 \text{ Myr}$  can be estimated using Eq. 2 of <sup>17</sup>. Here we have to make some assumption about the stellar mass function in the cluster, but for clarity adopting a mean mass of  $\langle m \rangle = 0.5 \text{ M}_\odot$  is sufficient without detailed knowledge of the exact shape of the initial mass function. For a reasonable range of cluster densities and distances from the center of NGC 1260 we can now calculate the mass that can be grown in the cluster in  $\lesssim 3 \text{ Myr}$ .

In Fig. 1 we present the results of our calculations using a King <sup>26</sup> model with a depth of the central potential expressed in the dimension-less parameter  $W_0 = 8$ , which can produce at most a  $\sim 920 \text{ M}_\odot$  star in a collision runaway. For shallower as well as for more concentrated King models the maximum mass for the supermassive star decreases, as well as the mass of the cluster that produces such stars.

The last collision before the supernova, must have occurred with a relatively un-

evolved main-sequence star, and deposited large quantities of hydrogen on the surface of the collision product. By the time of the supernova not all surface hydrogen of the last collision was blown away, as about one  $M_{\odot}$  of hydrogen was observed in the supernova <sup>5</sup>. The remainder of the hydrogen deposited on the stellar surface during the last collision was found in the interstellar medium surrounding the supernova, and exceeds some  $0.5\text{--}5 M_{\odot}$  <sup>7, 5</sup> but could be as high as  $20\text{--}30 M_{\odot}$  <sup>5</sup>. This mass may have come from the strong stellar wind in the last few  $10^4$  years before the supernova, blowing away the hydrogen which was deposited to the stellar surface during the collision. A tentative upper limit for the rate of mass loss of the progenitor star is  $\dot{m} = 5 \times 10^{-4} M_{\odot}/\text{yr}$  to  $1.4 \times 10^{-4} M_{\odot}/\text{yr}$  <sup>5</sup>. These observed mass loss rates are consistent with those of detailed evolutionary calculations of stars of  $500\text{--}1001 M_{\odot}$  <sup>27, 28</sup>. At this mass loss rate it takes roughly  $4 \times 10^4$  to  $1.4 \times 10^5$  years to blow  $20 M_{\odot}$  in the form of a stellar wind from the surface of the supermassive star. This time scale is of the same order as our estimated average time between collisions of  $\lesssim 7.3 \times 10^4$  years (see fig. 1).

The luminosity of the supernova explosion in collapsar models is driven by the angular momentum transfer from the critically rotating black hole to its surrounding torus. The available energy reservoir, and thus the supernova brightness, would then be proportional to the mass of the black hole <sup>29</sup>. The observed brightness of SN 2006gy would then be consistent with the collapse of an unusually massive star, and the consequent formation of a rather massive ( $\gtrsim 100 M_{\odot}$ ) black hole. We are unaware of detailed simulations of such an unusual supernova to bolster our arguments, but the consequences for the supernova seem to be profound and we encourage further research in this direction.

The amount of hydrogen in the pre-supernova stellar envelope, the amount of hydrogen in the interstellar medium, the mass-loss rate of the supernova progenitor derived from the observations and the enormous brightness of the supernova,

bracket the values we derive based on the collision runaway scenario. We therefore conclude that a collision of a  $\sim 20 M_{\odot}$  main-sequence star with a supermassive star  $\sim 10^5$  years before the supernova could conveniently explain the range of oddities surrounding SN 2006gy. We predict that a young ( $\lesssim 5$  Myr), dense and massive ( $10^4 \lesssim m \lesssim 10^5 M_{\odot}$ ) star cluster is present at the location of the supernova. At this moment the star cluster cannot be seen, but adopting a mass-to-light ratio of  $\sim 0.6$ , which is consistent with the Starburst99<sup>30</sup> models for a  $\lesssim 5$  Myr old stellar population, the cluster should become noticeable as soon as the supernova fades below an absolute magnitude of about -8.2 mag for  $10^5 M_{\odot}$  and -5.7 mag, for a  $10^4 M_{\odot}$  star cluster.

The environment in which the collision runaway can be initiated is rather exotic, as the cluster has to be sufficiently massive and dense to warrant dynamical core collapse within a few Myr. In star clusters sufficiently massive to grow a massive collision product there are typically between 60 and 600 stars  $> 8 M_{\odot}$ , and consequently only one out of 60–600 type Ib/c or type II supernovae in these clusters will be of this peculiar bright type, like SN 2006gy. If in a nuclear or a normal starburst ten per cent of all stars are formed in sufficiently dense clusters, one would expect that about one out of 600–6,000 supernovae to be of this type.

1. Quimby, R. Supernova 2006gy in NGC 1260. *Central Bureau Electronic Telegrams* **644**, 1–1 (2006).
2. Harutyunyan, A. *et al.* Supernova 2006gy in NGC 1260. *Central Bureau Electronic Telegrams* **647**, 1–1 (2006).
3. Prieto, J. L., Garnavich, P., Chronister, A. & Connick, P. 2006gy in NGC 1260. *Central Bureau Electronic Telegrams* **648**, 1–1 (2006).

4. Foley, R. J. *et al.* Supernova 2006gy in NGC 1260. *Central Bureau Electronic Telegrams* **695**, 1–1 (2006).
5. Smith, N. *et al.* SN 2006gy: Discovery of the most luminous supernova ever recorded, powered by the death of an extremely massive star like Eta Carinae. *ArXiv Astrophysics e-prints* **astro-ph/0002483** (2006).
6. Meynet, G. & Maeder, A. Stellar evolution with rotation. XI. Wolf-Rayet star populations at different metallicities. *Astron. & Astrophys.* **429**, 581–598 (2005).
7. Ofek, E. O. *et al.* SN 2006gy: An Extremely Luminous Supernova in the Galaxy NGC 1260. *Astrophys. J. Lett.* **659**, L13–L16 (2007).
8. Portegies Zwart, S. F., Makino, J., McMillan, S. L. W. & Hut, P. Star cluster ecology. III. Runaway collisions in young compact star clusters. *Astron. & Astrophys.* **348**, 117–126 (1999).
9. Suzuki, T. K. *et al.* Evolution of Collisionally Merged Massive Stars. *ArXiv Astrophysics e-prints* **astro-ph/0703290** (2007).
10. Fryer, C. L. & Kalogera, V. Theoretical black hole mass distributions. *Astrophys. J.* **554**, 548–560 (2001).
11. Portegies Zwart, S. F., Baumgardt, H., Hut, P., Makino, J. & McMillan, S. L. W. Formation of massive black holes through runaway collisions in dense young star clusters. *Nature* **428**, 724–726 (2004).
12. Cotera, A. S. *et al.* The Discovery of Hot Stars near the Galactic Center Thermal Radio Filaments. *Astrophys. J.* **461**, 750–761 (1996).
13. Cotera, A. S. *et al.* A New Cluster of Hot Stars near the Galactic Center. in *Bulletin of the American Astronomical Society*, 1262–1263, (1992).

14. Dutra, C. M. & Bica, E. "new star clusters projected close to the galactic centre". *Astron. & Astrophys.* **359**, L9–L12 (2000).
15. Dutra, C. M. *et al.* NTT infrared imaging of star cluster candidates towards the central parts of the Galaxy. *Astron. & Astrophys.* **408**, 127–134 (2003).
16. Maillard, J. P., Paumard, T., Stolovy, S. R. & Rigaut, F. The nature of the Galactic Center source IRS 13 revealed by high spatial resolution in the infrared. *Astron. & Astrophys.* **423**, 155–167 (2004).
17. Portegies Zwart, S. F. *et al.* The Ecology of Star Clusters and Intermediate-Mass Black Holes in the Galactic Bulge. *Astrophys. J.* **641**, 319–326 (2006).
18. Brunzendorf, J. & Meusinger, H. The galaxy cluster Abell 426 (Perseus). A catalogue of 660 galaxy positions, isophotal magnitudes and morphological types. *Astron. & Astrophys. Supp.* **139**, 141–161 (1999).
19. Wegner, G. *et al.* Redshift-Distance Survey of Early-Type Galaxies: Spectroscopic Data. *Astron. J.* **126**, 2268–2280 (2003).
20. Salucci, P., Ashman, K. M. & Persic, M. The dark matter content of spiral galaxies. *Astrophys. J.* **379**, 89–93 (1991).
21. Sanders, R. H. & Lowinger, T. The Distribution of Mass in the Galactic Nucleus. *Astron. J.* **77**, 292–297 (1972).
22. Binney, J. & Tremaine, S. *Galactic dynamics*. Princeton, NJ, Princeton University Press, pp.747, (1987).
23. Portegies Zwart, S. F. & McMillan, S. L. W. The Runaway Growth of Intermediate-Mass Black Holes in Dense Star Clusters. *Astrophys. J.* **576**, 899–907 (2002).

24. Gürkan, M. A., Freitag, M. & Rasio, F. A. Formation of Massive Black Holes in Dense Star Clusters. I. Mass Segregation and Core Collapse. *Astrophys. J.* **604**, 632–652 (2004).
25. Freitag, M., Gürkan, M. A. & Rasio, F. A. Runaway collisions in young star clusters - II. Numerical results. *Mon. Not. R. Astron. Soc.* **368**, 141–161 (2006).
26. King, I. R. The structure of star clusters. iii. some simple dynamical models. *Astron. J.* **71**, 64–75 (1966).
27. Yungelson, L. R. Evolution of Ultra-Massive Stars and its Implications. *Calibrating the Top of the Stellar M-L Relation, 26th meeting of the IAU, Joint Discussion 5, 16 2006, Prague, Czech Republic, JD05, #9* **5** (2006).
28. Yungelson, L. R., van den Heuvel, E., Vinck, J., Portegies Zwart, S. & de Koter, A. On the evolution and fate of supermassive stars. *Submitted to A&A* (2007).
29. Lee, H. K., Wijers, R. A. M. J. & Brown, G. E. The Blandford-Znajek process as a central engine for a gamma-ray burst. *Phys Rep.* **325**, 83–114 (2000).
30. Leitherer, C. *et al.* Starburst99: Synthesis Models for Galaxies with Active Star Formation. *Astrophys. J. Supp.* **123**, 3–40 (1999).

## Acknowledgments

This work was supported by NWO under grant No. 643.200.503, the Netherlands Research School for Astronomy (NOVA) and the National Science Foundation under grant No. PHY 05-51164 to the Kavli Institute for Theoretical Physics in Santa Barbara.



Figure 1: Mass of the collision runaway star as a function of cluster mass and its distance to the center of NGC 1260. The contours, computed for a King model with  $W_0 = 8$ , give the mass of the runaway collision star as a function of the distance to the center of the galaxy NGC 1260 and the mass of the star cluster. The lowest four contours are labeled by the mass of the supermassive star (in solar masses) with constant increments of  $100 M_\odot$  for subsequent curves. A star cluster less massive than about  $6,000 M_\odot$  is unable to experience core collapse and produce a collision runaway before it dissolves in the tidal field of the parent galaxy, whereas star clusters in the top right corner are unable to reach core collapse before the most massive stars experience a supernova. The most massive object that can form is  $\sim 920 M_\odot$  in a  $m = 1.3 \times 10^5 M_\odot$  cluster. A  $m = 48,000 M_\odot$  cluster with  $W_0 = 5$  can maximally produce a  $340 M_\odot$  supermassive star, whereas a King model with  $W_0 = 11$  can produce a star of at most  $480 M_\odot$  in a cluster of  $68,000 M_\odot$ . With an average mass increase per collision of  $\sim 20 M_\odot$ <sup>8, 23</sup>, the supermassive star then has experienced at most some 40 collisions between the moment of gravothermal collapse of the cluster core and the moment that the supermassive star explodes in a supernova. The mean time between collisions for this model is then  $\lesssim 7.3 \times 10^4$  years. For shallower as well as for more concentrated models the time between collisions is larger;  $\lesssim 1.7 \times 10^5$  years for  $W_0 = 5$  and  $\lesssim 1.2 \times 10^5$  years for  $W_0 = 11$ . For a wide range of reasonable cluster parameters it appears likely that a collision runaway ensues and produces a supermassive star.

